



## NEWS & VIEWS

# Is Inflammation a Mitochondrial Dysfunction-Dependent Event in Fibromyalgia?

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### Abstract

Fibromyalgia (FM) is a complex disorder that affects up to 5% of the general population worldwide. Both mitochondrial dysfunction and inflammation have been implicated in the pathophysiology of FM. We have investigated the possible relationship between mitochondrial dysfunction, oxidative stress, and inflammation in FM. We studied 30 women diagnosed with FM and 20 healthy women. Blood mononuclear cells (BMCs) from FM patients showed reduced level of coenzyme Q<sub>10</sub> (CoQ<sub>10</sub>) and mtDNA contents and high level of mitochondrial reactive oxygen species (ROS) and serum tumor necrosis factor (TNF)-alpha and transcript levels. A significant negative correlation between CoQ<sub>10</sub> and TNF-alpha levels ( $r = -0.588$ ;  $p < 0.01$ ), and a positive correlation between ROS and TNF-alpha levels ( $r = 0.791$ ;  $p < 0.001$ ) were observed accompanied by a significant correlation of visual analogical scale with serum TNF-alpha and transcript levels ( $r = 0.4507$ ;  $p < 0.05$  and  $r = 0.7089$ ;  $p < 0.001$ , respectively). TNF-alpha release was observed in an *in vitro* (BMCs) and *in vivo* (mice) CoQ<sub>10</sub> deficiency model. Oral CoQ<sub>10</sub> supplementation restored biochemical parameters and induced a significant improvement in clinical symptoms ( $p < 0.001$ ). These results lead to the hypothesis that inflammation could be a mitochondrial dysfunction-dependent event implicated in the pathophysiology of FM in several patients indicating at mitochondria as a possible new therapeutic target. *Antioxid. Redox Signal.* 18, 800–807.

### Introduction

**F**IBROMYALGIA (FM) is a common chronic pain syndrome accompanied by other symptoms such as fatigue, headache, sleep disturbances, and depression, the pathophysiological mechanisms of which have not yet been identified. Although FM is diagnosed according to the classification criteria established by the American College of Rheumatology (ACR) (9), the diagnosis is not easy and may be frequently overlooked; this is why new diagnostic markers in FM are needed. Therefore, despite being a common disorder that affects at least 5 million individuals only in the United States (9), its pathogenic mechanism remains elusive. There are some hypotheses and pilot studies suggesting that cytokines may play an important role in FM (8), and correlation has

been observed between cytokines and several symptoms common in FM (8). However, there are discrepant findings related to whether pro-inflammatory and anti-inflammatory cytokines are elevated or reduced in people with FM and whether their levels correlate with the core symptoms of this disorder (8).

Reactive oxygen species (ROS) have an established role in inflammation and host defense, and are involved in the pathophysiology of several diseases including rheumatoid arthritis, multiple sclerosis, and diabetes (1). Moreover, in addition to the presence of oxidative stress, these diseases are also characterized by deregulated inflammatory responses including, but not limited to, pro-inflammatory cytokine production.

It is believed, that in cells undergoing aerobic metabolism, the majority of ROS are produced as a byproduct of the

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**Innovation**

Inflammation has been indicated as being in the pathophysiology of fibromyalgia (FM) in some patients, and it has been suggested that oxidative stress and mitochondria could be among the factors responsible for development of inflammation. This is an interesting issue that warrants consideration to design new experiments to gain further insight into its potential therapeutic applications, given that systemic antioxidant status is an exogenously modifiable factor. The results described in this article may serve as a new way for designing experiments to better understand the influence of oxidative stress on the development of FM and generate new therapeutic strategies.

mitochondrial electron transport chain (1,7). In this respect, coenzyme Q<sub>10</sub> (CoQ<sub>10</sub>), a small lipophilic molecule located in the inner mitochondrial membrane, transfers reducing equivalents from complexes I and II to complex III. It has been widely demonstrated that CoQ<sub>10</sub> is essential for mitochondrial chain efficiency, and evidence exists that it affects the expression of genes involved in inflammatory pathways (6). Recently, we demonstrated CoQ<sub>10</sub> deficiency, mitochondrial dysfunction, oxidative stress, and mitophagy in blood mononuclear cells (BMCs) from FM patients (2).

This study examined the hypothesis that inflammation in FM could be induced under conditions of mitochondrial dysfunction and oxidative stress. We carried out these studies with the aim of determining mitochondrial dysfunction, oxidative stress, CoQ<sub>10</sub> levels, in addition to serum tumor necrosis factor (TNF)-alpha levels and mRNA expression levels of TNF-alpha in BMCs from FM patients. Further, we induced CoQ<sub>10</sub> deficiency in BMCs from healthy controls to evaluate TNF-alpha production, and analyzed the inflammation activation in a mouse model of CoQ<sub>10</sub> deficiency. Finally, in FM volunteers, we studied the effects of oral CoQ<sub>10</sub> supplementation on TNF-alpha levels and FM symptoms.

**Results and Discussion**

Mean age in the FM group was  $43.8 \pm 13.1$  years and in the control group it was  $44.9 \pm 10$ . Patient routine laboratory tests yielded normal results (data not shown). The mean duration of symptoms in the FM group was  $8.2 \pm 4.4$  years. The mean tender point score in the FM group was  $15.1 \pm 2.2$  points (Table 1).

TABLE 1. CHARACTERISTIC FINDINGS OF FIBROMYALGIA PATIENTS AND CONTROL GROUP

	Patients N = 30	Controls N = 20
Age (years)	$43.8 \pm 13.1$	$44.9 \pm 10$
Tender points	$15.1 \pm 2.2$	0
Duration of disease (years)	$8.2 \pm 4.4$	0
BMI (kg/m <sup>2</sup> )	$25.8 \pm 3.3$	$24.6 \pm 2.1$
VAS total score	$6.9 \pm 0.8^a$	$0.4 \pm 0.1$
FIQ total score, range 0–80	$56.1 \pm 11.1^a$	$2.1 \pm 1.1$

<sup>a</sup> $p < 0.001$ .

BMI, Body Mass Index; FIQ, Fibromyalgia Impact Questionnaire; VAS, Visual Analogical Scale.

### *BMCs from FM patients show evidences of mitochondrial dysfunction*

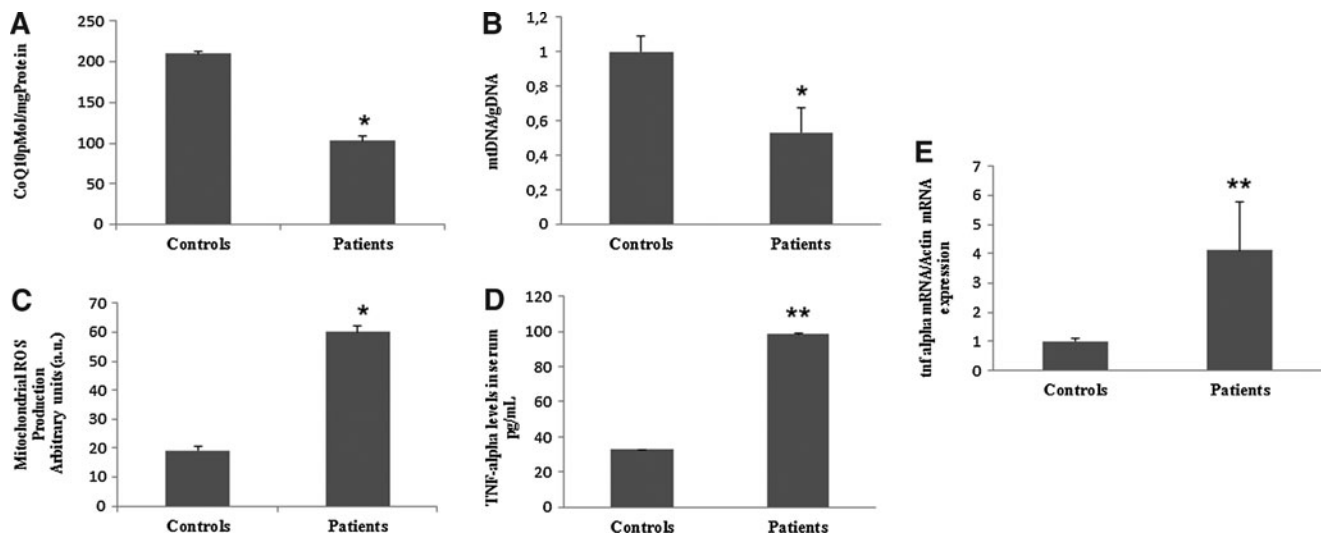
Mitochondrial dysfunction has recently been proposed as a relevant event in the pathogenesis of this disorder (2). Mitochondria generate energy primarily in the form of electrochemical proton gradient, which fuels ATP production, ion transport, and metabolism. At the same time, mitochondria are also the major source of ROS. Both complexes I and III, along with CoQ<sub>10</sub> leak electrons to oxygen (7). CoQ<sub>10</sub> deficiency has been associated with a variety of human disorders, some of them caused by a direct defect of CoQ<sub>10</sub> biosynthesis genes or as a secondary consequence of other diseases (7). Recent findings have shown that CoQ<sub>10</sub> deficiency alters mitochondria function and mitochondrial respiratory complexes organization, leading to increased ROS generation and activation of mitochondrial transition pore, increasing autophagy of dysfunctional mitochondria by mitophagy (2,7).

Since it has been suggested that CoQ<sub>10</sub> levels could be a useful biological marker of mitochondrial function (2,7), we measured CoQ<sub>10</sub> levels (Fig. 1A) in BMCs from healthy controls and FM patients as a feature of mitochondrial dysfunction. BMCs from FM patients showed a decrease of CoQ<sub>10</sub> levels compared with controls (51% reduction of the average controls value, Fig. 1A). Further, significant decrement in mtDNA content in BMCs from FM patients was also observed (46.7% of the value found in the control group, Fig. 1B).

On one hand, it is known that mitochondrial dysfunction is often associated with an induction of ROS production in mitochondria and on the other hand, oxidative stress has been proposed as a relevant event in the pathogenesis of FM (2,4). To assess the oxidative stress level, we determined mitochondrial ROS in BMCs from FM patients and controls. On average, FM patients showed higher levels of mitochondrial ROS production in BMCs compared with control subjects (Fig. 1C).

### *Inflammation in FM patients is modulated by mitochondrial dysfunction*

Several hypotheses have been made around the etiological origin of FM and its symptoms. Clinical studies have produced evidence that FM may be associated with immune dysregulation of circulatory levels of pro-inflammatory cytokines, affecting the neural dysfunction of pain-related neurotransmitters (8). Cytokines, depending on their concentration, induce symptoms, such as fatigue, fever, sleep, pain, and myalgia (8), all of which usually developed in FM patients. Alterations in pro-inflammatory cytokine levels have been observed in serum and biopsies of FM patients (8). In addition, increased levels of IL-1Ra and IL-6 have been found in the supernatants of cells from FM patients *in vitro* (8). To assess inflammation in FM patients, we determined TNF-alpha levels in serum from controls and FM patients. FM patients showed higher level of TNF-alpha in serum compared with control subjects (Fig. 1D). Further, to corroborate inflammation in FM patients we analyzed the expression of *tnf-alpha* mRNA. Transcripts of *tnf-alpha* increased in BMCs from FM patients (Fig. 1E). Recent evidence has shown the possible involvement of ROS in inflammation suggesting that mitochondrial ROS may be a novel therapeutic target for inflammatory diseases. (1). In this respect, inflammation as a consequence of oxidative stress and mitochondrial dysfunction has been indicated as the cause of many human diseases



**FIG. 1.** Coenzyme  $Q_{10}$  (CoQ $_{10}$ ) levels, mitochondrial reactive oxygen species (ROS) production, and tumor necrosis factor (TNF)- $\alpha$  levels in blood mononuclear cells (BMCs) from fibromyalgia (FM) patients and healthy control individuals. **(A)** CoQ $_{10}$  levels were measured by high-performance liquid chromatography, as described in Materials and Methods. **(B)** Reduced mtDNA contents in BMCs from FM patients compared with healthy controls. **(C)** Mitochondrial ROS production was analyzed in BMCs from controls and FM patients by flow cytometry as described in Material and Methods. **(D)** Serum TNF- $\alpha$  levels in FM and control patients were measured as described in Material and Methods. **(E)** tnfr- $\alpha$  transcripts were analyzed by SYBR Green quantitative polymerase chain reaction as described in Materials and Methods. Data represent the mean  $\pm$  SD of three separate experiments. \* $p < 0.001$ ; \*\* $p < 0.05$  between controls and FM patients.

[e.g. dyslipidemia, thrombosis, metabolic syndrome, diabetes, macular degeneration, and neurodegenerative diseases such as Alzheimer's (1)]. Interestingly, we observed an important negative correlation between CoQ $_{10}$  and TNF- $\alpha$  levels ( $r = -0.588$ ;  $p < 0.01$ ), and a positive correlation between ROS and TNF- $\alpha$  levels ( $r = 0.791$ ;  $p < 0.001$ ) (Fig. 2A, B). Also, both TNF- $\alpha$  peptide and mRNA levels showed high positive correlations with pain scale scores of FM patients (Fig. 2C, D). These data suggest that high cytokine levels may be involved in the pathophysiology of FM and underline an important role of oxidative stress and mitochondrial dysfunction in the inflammatory process in FM.

#### Induced CoQ deficiency leads to mitochondrial ROS production and TNF- $\alpha$ synthesis

To verify the role of CoQ $_{10}$  in the increase to TNF- $\alpha$  levels observed in FM patients, we induced CoQ $_{10}$  deficiency by inhibiting endogenous biosynthesis in BMCs from healthy controls with P-aminobenzoate (PABA) treatment, a competitive inhibitor of polyprenyl-4-hydroxybenzoate transferase (Coq2p) (7), *in vitro* assay (Fig. 3A). PABA treatment affected oxidative stress, inducing an increment of mitochondrial ROS levels ( $p < 0.001$ ) (Fig. 3B). CoQ deficiency provoked an important increment of TNF- $\alpha$  in the supernatant of cell cultures (Fig. 3C). Since CoQ $_{10}$  is also an important antioxidant, we evaluated the effect of treatment with CoQ $_{10}$  and other antioxidants in the *in vitro* model of CoQ $_{10}$  deficiency. BMCs were incubated with PABA in the presence or absence of three antioxidants, CoQ $_{10}$ ,  $\alpha$ -tocopherol ( $\alpha$ -toc), and N-acetylcysteine (N-Acet). Mitochondrial ROS and TNF- $\alpha$  production were then measured. CoQ $_{10}$  attenuated ROS production ( $p < 0.001$ ) more significantly than  $\alpha$ -toc and N-acet ( $p < 0.05$ ).

CoQ $_{10}$  has been shown to have a connection with inflammation: a significant negative correlation has been observed

between CoQ $_{10}$  and pro-inflammatory markers in septic shock patients (1). Moreover, expression profiling revealed that CoQ $_{10}$  influences the expression of inflammatory genes suggesting that CoQ $_{10}$  exerts anti-inflammatory properties (6). This influence has been associated *via* NF-kappaB-dependent gene expression. Immunohistochemical studies in FM tissues revealed a stronger expression of NF-kappaB in muscle (5), and TNF- $\alpha$  is an NF-kappaB-dependent pro-inflammatory cytokine (1).

To study the role of CoQ $_{10}$  in the pathogenesis of FM and inflammatory process, and according to *in vitro* results, we induced a partial depletion of CoQ $_{10}$  in mice by sub-chronic PABA administration. CoQ depletion might provoke an increment of serum TNF- $\alpha$  in mice with respect to controls (Fig. 4A). When compared with vehicle-treated controls, PABA-injected mice showed an increase in serum TNF- $\alpha$  levels (Fig. 4B), and, interestingly, also showed high levels of hyperalgesia and reproduced a correlation between TNF- $\alpha$  levels and pain. Finally, TNF- $\alpha$  levels showed an important correlation with pain assayed in mice, (negative correlation between TNF- $\alpha$  and time latency in hot plate test response,  $r = -0.6187$ ;  $p < 0.01$ ).

#### Oral CoQ $_{10}$ supplementation in FM patients reduced TNF- $\alpha$ levels and improved clinical symptoms

According to our results, oxidative stress, mitochondrial dysfunction, and also CoQ $_{10}$  could play a role in the inflammatory response found in FM. CoQ $_{10}$  may have two roles in this pathological process: first of all, CoQ $_{10}$  is a mitochondrial cofactor with the potential to boost mitochondrial function and, second, CoQ $_{10}$  is a powerful free radical scavenger that can mitigate lipid peroxidation and DNA damage caused by oxidative stress (3). To study the possible effect of oral CoQ $_{10}$  supplementation in inflammatory process and mitochondrial

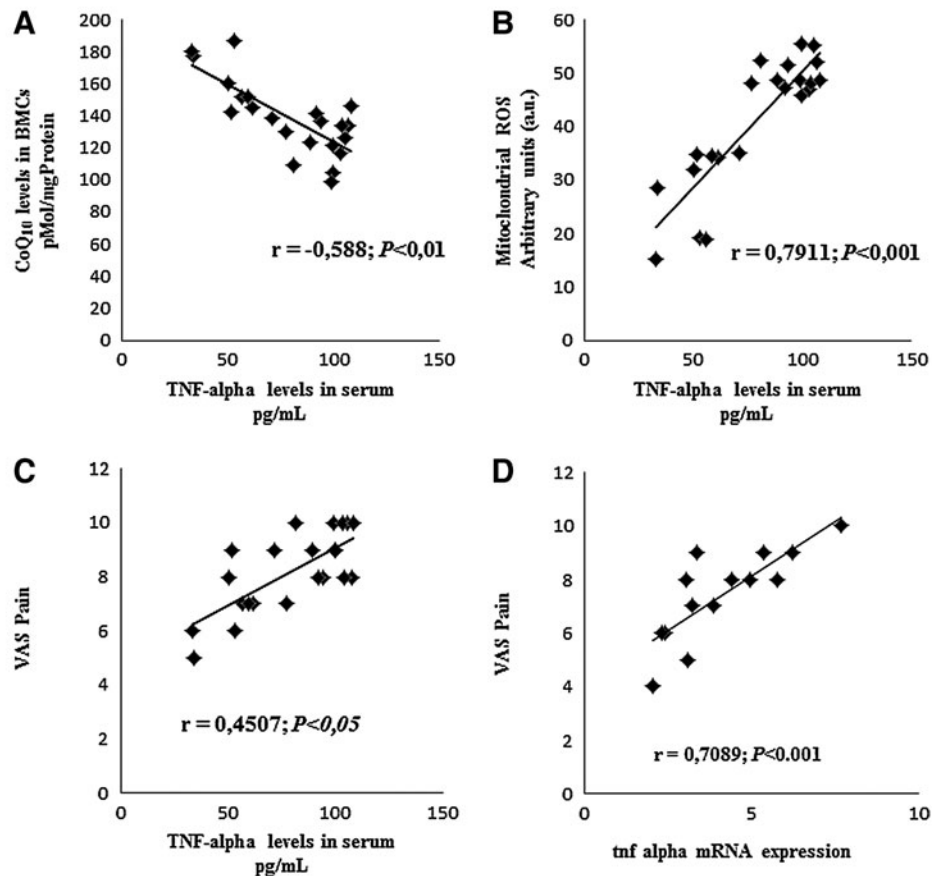


FIG. 2. Correlations of: serum TNF- $\alpha$  versus CoQ<sub>10</sub> (A), or versus mitochondrial ROS (B), and serum TNF- $\alpha$  and transcript tnf- $\alpha$  versus pain in FM patients (C and D). The correlations were established by calculating correlation coefficients.

dysfunction of FM and evaluate the improvement in clinical symptoms, eight volunteer FM patients were supplemented with CoQ<sub>10</sub>. CoQ<sub>10</sub> supplementation counteracted lipid peroxidation ( $p < 0.001$ ), and it restored CoQ<sub>10</sub> levels and mtDNA content in BMCs from FM patients ( $p < 0.001$ ). Interestingly, TNF- $\alpha$  levels were significantly reduced together with a marked improvement in FM clinical symptoms (Table 2).

Our patients, after oral CoQ<sub>10</sub> supplementation showed an important improvement in clinical FM symptoms, reduced levels of TNF- $\alpha$  and lipid peroxidation, indicating once again the possible role of CoQ<sub>10</sub> in the pathogenesis of FM. In other conditions of inflammation and oxidative stress, such as in the case of strenuous exercise, CoQ<sub>10</sub> supplementation before exercise has been shown to decrease oxidative stress and modulate inflammatory signaling, reducing the subsequent muscle damage (1). CoQ<sub>10</sub> analogues, such as mitoquinone, block transcription of inflammatory cytokines involved in the mitochondrial ROS-dependent inflammatory process (1).

### Concluding Remarks and Future Directions

Most studies that have up to now examined the role of inflammation in FM have been incomplete and contradictory showing several discrepancies (8). However, according to

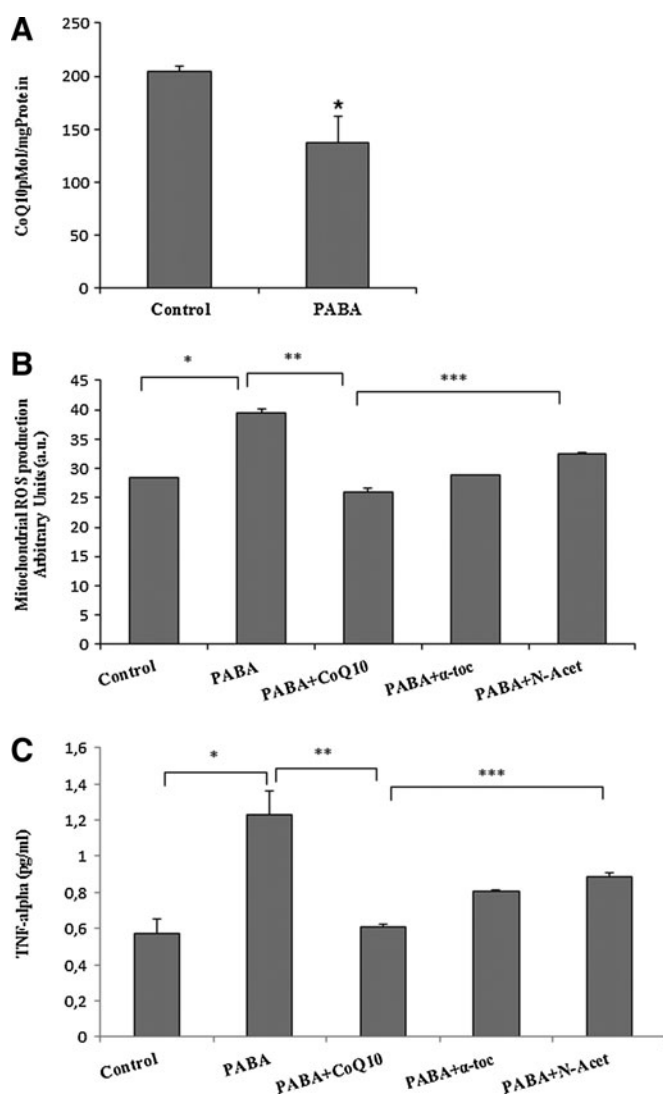
these results, the correlation between TNF- $\alpha$ , CoQ<sub>10</sub>, and mitochondrial ROS levels may explain that inflammation in several FM patients could depend on mitochondrial dysfunction, thus identifying a new subgroup of patients in FM. Increased mitochondrial ROS in FM would result from enhanced oxidative phosphorylation. Recently, we demonstrated that oxidative stress could be implicated in the severity of clinical symptoms in FM (2), therefore, antioxidant therapy should be examined as a possible treatment in FM. Blockade of ROS production by mitochondria would provide a new therapeutic strategy to decrease symptoms in FM and other inflammatory states. Moreover, CoQ<sub>10</sub> treatment could be used as an alternative therapy in FM and this should be the aim of further studies. Further analysis involving double-blind placebo-controlled clinical trials will be required to confirm this observation. Indeed, our research group is currently working in this direction, on the basis of the conclusions of the exploratory work discussed in this article.

### Notes

#### Ethical statements

Written informed consent and the approval of the ethical committee of the University of Seville were obtained, according to the principles of the Declaration of Helsinki.



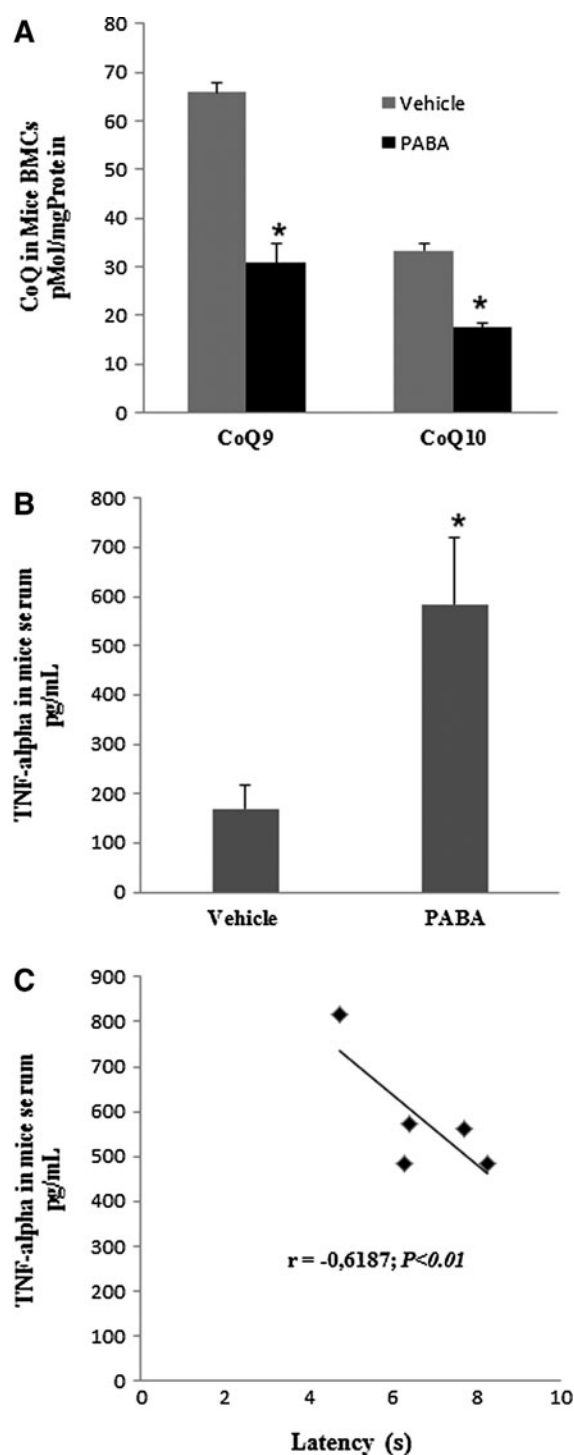


**FIG. 3.** Induced CoQ deficiency *in vitro* leads to mitochondrial ROS production and TNF- $\alpha$  release. 1 mM of P-aminobenzoate (PABA) induced partial CoQ<sub>10</sub> deficiency (A), and high levels of mitochondrial ROS production, being restored by antioxidants (B). CoQ deficiency provoked an important increment of TNF- $\alpha$  in the supernatant of cell cultures, counteracted by antioxidants (C). CoQ<sub>10</sub> produced a more significant protection than other antioxidants. Data represent the mean  $\pm$  SD of three separate experiments. \* $p$  < 0.001 between control and PABA; \*\* $p$  < 0.01 between PABA with absence or presence of CoQ<sub>10</sub>; \*\*\* $p$  < 0.05 between presence of CoQ<sub>10</sub> or presence of BHA or N-acetylcysteine.

Pain studies in mice were performed in accordance with the European Union guidelines (86/609/EU) and Spanish regulations for the use of laboratory animals in chronic experiments (BOE 67/8509-12, 1988). All experiments were approved by the local institutional animal care committee.

#### Patients

The study consisted of 30 women diagnosed with FM and 20 healthy women. Inclusion criteria were FM that had been diagnosed in the previous 2 to 3 years, based on the current ACR diagnostic criteria (9). Exclusion criteria were acute



**FIG. 4.** TNF- $\alpha$  release in a partial CoQ<sub>10</sub> depletion mice model. PABA was administered at a dose of 20 mg/kg/day for 15 days. (A) Levels of CoQ<sub>9</sub> and CoQ<sub>10</sub> measured in BMCs from mice treated with vehicle or PABA (mammalian species such as the mouse and the rat that have a relatively short lifespan primarily contain CoQ<sub>9</sub> and low levels of CoQ<sub>10</sub>). Data represent the mean  $\pm$  SD of three separate experiments. \* $p$  < 0.001 of CoQ<sub>9</sub> and CoQ<sub>10</sub> between vehicle or PABA. (B) TNF- $\alpha$  levels were measured in serum from mice treated with the vehicle or PABA. Data represent the mean  $\pm$  SD of three separate experiments. \* $p$  < 0.001 between vehicle or PABA. (C) Correlation of TNF- $\alpha$  serum levels and pain in animal model. ( $n$  = 5 per group).

TABLE 2. CLINICAL SYMPTOMS AFTER COENZYME Q<sub>10</sub> TREATMENT

	Pretreatment N = 8	Post-treatment N = 8	Controls N = 20
Tender points	14 ± 1.2	7.9 ± 1.6 <sup>a</sup>	-
FIQ total score, range 0–80	56 ± 3.2	32.9 ± 2.2 <sup>a</sup>	2.1 ± 1.1
VAS, range 0–10	6.6 ± 0.5	3.6 ± 0.6 <sup>a</sup>	0.4 ± 0.1
CoQ <sub>10</sub> (pmol/mg protein)	102.6 ± 21.9	201.9 ± 32.1 <sup>a</sup>	209.6 ± 3.5
mtDNA content	0.4 ± 0.1	0.9 ± 0.1 <sup>a</sup>	1 ± 0.09
LP in BMCs (nmol/million cells)	25.1 ± 8.1	9.3 ± 3.2 <sup>a</sup>	6.8 ± 1.9
TNF-α (pg/ml)	82.5 ± 11.2	31.9 ± 9.9 <sup>a</sup>	32.6 ± 0.05

Values are mean ± SD.

<sup>a</sup>*p* < 0.001 between pre- and post-treatment.

CoQ<sub>10</sub>, Coenzyme Q<sub>10</sub>; mtDNA, mitochondrial DNA; LP, lipid peroxidation; BMCs, blood mononuclear cells; TNF, tumor necrosis factor.

infectious diseases in the previous 3 weeks; past or present neurological, psychiatric, metabolic, autoimmune, allergy-related, dermal, or chronic inflammatory diseases; undesired habits (*e.g.*, smoking, alcohol, etc.); oral diseases (*e.g.*, periodontitis); medical conditions that required glucocorticoid treatment, use of analgesics, statin, or antidepressant drugs; past or current substance abuse or dependence; and pregnancy or current breastfeeding. Healthy controls had no signs or symptoms of FM and were free of any medication for at least 3 weeks before the study began. All patients and controls had taken no drugs or vitamin/nutritional supplements during the 3 weeks prior to the collection of blood samples. However, before the study, patients reported they used paracetamol on demand. Clinical data were obtained from physical examination and evaluated using the Fibromyalgia Impact Questionnaire (FIQ) including visual analogue scales regarding general and diffuse pain typical of FM (visual analogical scale [VAS]).

#### Animals and drug administration

Two groups (control and treated) of 5 six-week-old male Swiss mice weighing 25–30 g were maintained on a 12 h light/dark cycle. PABA, a competitive inhibitor of polyprenyl-4-hydroxybenzoate transferase (7), was dissolved in saline (vehicle) and intra-peritoneally administered at a dose of 20 mg/Kg/day for 15 days. Behavioral tests were performed 5 days after the first drug administration. After testing, mice were anesthetized with CO<sub>2</sub> and sacrificed by decapitation. Blood samples were collected for immediate biochemical analysis and BMCs were isolated.

#### BMC cultures

BMCs were purified from heparinized blood by isopycnic centrifugation using Histopaque-1119 and Histopaque-1077 (Sigma Chemical Co.). BMCs were cultured at 37°C in a 5% CO<sub>2</sub> atmosphere in RPMI-1640 medium supplemented with L-glutamine, an antibiotic/antimycotic solution (Sigma Chemical Co.), and 10% fetal bovine serum.

#### Induction of CoQ<sub>10</sub> Deficiency

Partial CoQ<sub>10</sub> deficiency was induced by inhibiting endogenous biosynthesis in BMCs from healthy controls by treatment with PABA (Sigma Chemical Co.), a competitive inhibitor of polyprenyl-4-hydroxybenzoate transferase (7). To achieve this, cells were cultured for 24 h in the presence of 1 mM PABA, or

alternatively PABA + 10 μM CoQ<sub>10</sub>, PABA + 30 μM α-toc, and PABA + 10 mM N-Acet (Sigma Chemical Co.).

#### TNF-α levels

TNF-α levels in serum from control and patients, and mice were assayed in duplicates by commercial ELISA kits (ELISA, Biosource).

#### CoQ<sub>10</sub> levels determination

CoQ<sub>9</sub> was used as an internal standard in human assay and CoQ<sub>6</sub> in mice assay. The cell samples were lysed with 1% SDS and vortexed for 1 min. A mixture of ethanol:isopropanol (95:5) was added and the samples were vortexed for 1 min. To recover CoQ, 5 ml of hexane was added and the samples were centrifuged at 1000 g for 5 min at 4°C. The upper phases from three extractions were recovered and dried on a rotator evaporator. The lipid extract was suspended in 1 ml of ethanol, dried in a speed vac, and kept at –20°C. Samples were suspended in a suitable volume of ethanol before high-performance liquid chromatography (HPLC) injection. Lipid components were separated by a Prominence Shimadzu HPLC system (Shimadzu Scientific Instruments) equipped with a Shimadzu Shim-pack XR-ODS column. CoQ levels were analyzed using an ultraviolet SPD-20A detector.

#### Mitochondrial ROS production

Mitochondrial ROS generation in BMCs was assessed by MitoSOX™ (Invitrogen/Molecular Probes), a red mitochondrial superoxide indicator. BMCs were incubated with 1 μM MitoSox for 30 min at 37°C and washed twice with PBS. Cells were analyzed by flow cytometry. To assay ROS production with antioxidants, BMCs were incubated for 24 h with 10 μM CoQ<sub>10</sub>, (Pharma Nord), 30 μM α-toc, and 10 mM N-Acet (Sigma Chemical Co.).

#### Quantification of mtDNA

Nucleic acids were extracted from BMCs by standard cellular lysis. The primers used were as follows: for mitochondrial DNA, mtF3212 (5'-CACCCAAGAACAGGGTTTGT-3') and mtR3319 (5'-TGGCCATGGGTATGTTGTTAA-3') and those for nuclear DNA for loading normalization, 18S rRNA gene 18S1546F (5'-TAGAGGGACAAGTGGCGTTC-3') and 18S1650R (5'-CGCTGAGCCAGTCAGTGT-3'). Arbitrary units were computed as the ratio between the optical density band

corresponding to the mitochondrial DNA studied in the 20–30th cycle and that of nuclear DNA in the 15th amplification cycle. One unit was considered to be the ratio corresponding to the control patient.

#### Lipid peroxidation

Lipid peroxidation in cells was determined by analyzing the accumulation of lipoperoxides using a commercial kit from Cayman Chemical. TBARS are expressed in terms of malondialdehyde levels.

#### Real-time quantitative polymerase chain reaction

The expression of *tnf-alpha* gene was analyzed by SYBR Green quantitative polymerase chain reaction using mRNA extracts of BMCs from patients and controls. The thermal cycling conditions used were as follows: denaturation at 95°C for 20 s, alignment at 54°C for 20 s, and elongation at 72°C for 20 s, for 40 cycles. *Tnf-alpha* primers were as follows: 5'-GCT GCA CTT TGG AGT GAT CG-3' (forward) and 5'-CTT ACC TAC AAC ATG GGC TAC AG-3' (reverse). As an internal control, we used *beta-actin* primers; forward: 5'-CCA GAT CAT GTT TGA GAC C-3' and reverse: 5'-ATG TCA CGC ACG ATT TCC C-3'. All reactions were performed in duplicate. Reaction mixtures without RNA were used as negative controls in each run.

#### Behavior studies of pain sensibility in mice

For the hot-plate test, a glass cylinder (16 cm high and 16 cm in diameter) was used to retain the mice on the heated surface of the plate, which was kept at the temperature of 45°C ± 0.5°C, 50°C ± 0.5°C, or 52.5°C ± 0.5°C. The time latency for paw-licking was measured. The cut-off for licking responses was 30 s. For the tail flick test, a thermostatic water bath was kept at a temperature of 48°C ± 0.5°C. The time latency for tail reflex was measured. The cut-off for responses was 15 s.

#### Oral CoQ<sub>10</sub> supplementation

Eight volunteer patients were supplemented with CoQ<sub>10</sub> (purchased from Pharma Nord), in soft gel capsules for 3 months (300 mg/day CoQ<sub>10</sub> divided into three doses). After 3 months of treatment, heparinized blood samples were collected after 12-h fasting and 24 h after the last dose, and clinical symptoms were evaluated. The CoQ<sub>10</sub> formulation consisted of soft gelatin capsules containing 100 mg of ubiquinone emulsified with diglycerol monooleate, beeswax, soy lecithin, and canola oil.

#### Statistical analysis

Data in figures are given as mean ± SD. Data between different groups were statistically analyzed by using analysis of variance (ANOVA) on Ranks with Sigma Plot and Sigma Stat statistical software (SPSS for Windows, 19, 2010, SPSS Inc.). For cell-culture studies, Student's *t* test was used for data analyses. A value of *p* < 0.05 was considered significant. To compare the behavioral results from animals treated with vehicle alone or with PABA a two-way variance (ANOVA) analysis was used. Statistical analyses included Pearson's correlations between CoQ<sub>10</sub> levels and mitochondrial ROS levels in BMCs compared with TNF- $\alpha$ , and between VAS pain compared with serum TNF- $\alpha$  peptide and mRNA.

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**Abbreviations Used**

$\alpha$ -toc = alpha-tocopherol  
ACR = American College of Rheumatology  
ANOVA = analysis of variance  
BMCs = blood mononuclear cells  
BMI = Body Mass Index  
CoQ<sub>10</sub> = Coenzyme Q<sub>10</sub>

FM = fibromyalgia  
HPLC = high-performance liquid chromatography  
MDA = malondialdehyde  
N-acet = N-acetylcysteine  
PABA = P-aminobenzoate  
ROS = reactive oxygen species  
TNF = tumor necrosis factor  
VAS = visual analogical scale